NASA

Technical Memorandum 79535

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(NASA-TM-79535) GAMMA-RAY ASTRONOMY AND THE ORIGIN OF COSMIC RAYS (NASA) 34 p HC A03/MF A01 CSCL 03B

N78-22017

Unclas

G3/93 16350

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APRIL 1978

National Aeronautics and
Space Administration

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Gamma-Ray Astronomy and the Origin of Cosmic Rays

by

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New surveys of galactic gamma-ray emission together with millimeter wave radio surveys indicate that cosmic rays are produced as the result of supernova explosions in our Galaxy with the most intense production occurring in a Great Galactic Ring about 35,000 light years in diameter where supernova remnants and pulsars are concentrated.

A NEW ASTRONOMY

Cosmic gamma-radiation is the most energetic natural form of electromagnetic radiation known to man. Such radiation is produced by cosmic rays: electrons and atomic nuclei which were born in deep space "accelerators", created by processes which we have only recently begun to guess. Cosmic gamma-rays can also be produced in giant supernova explosions, by the incredibly dense collapsed stellar objects known as pulsars, and in the intense gravitational fields around black holes, the ghost-objects predicted by general relativity, whose gravitational fields are so strong that no light can escape from them. Extragalactic gamma-rays may also be coming from times long ago around galaxies far away where matter and antimatter could have been annihilating each other even before the Sun was born.

The advent of the space age has made possible a new branch of astronomy, gamma-ray astronomy. While it has been possible to do some gamma-ray astronomy from high altitude balloons, observations of cosmic gamma-rays can best be made from detectors or gamma-ray "telescopes" placed aboard satellites and space probes. Cosmic gamma-radiation can reach us from the most distant parts of the Galaxy and the Universe, but when this radiation enters the Earth's atmosphere, it not only gets absorbed before reaching the ground, but it also gets lost amid a sea of terrestrial gamma-rays created in the atmosphere by cosmic ray bombardment. For these reasons, gamma-ray astronomy cannot be done from the ground and it is even difficult to do from high altitude balloons.

Undiscovered gamma-ray objects and astrophysical processes yet unknown are waiting to be explored, perhaps by the next generation of gamma-ray telescopes to be made possible by the space shuttle. But we have already begun to learn much, particularly about the origin of cosmic rays and also about the structure of our Galaxy--and this is the subject of this article.

THE GALAXY SEEN IN γ-RAYS

Because we are inside of it, we know much less about the structure of our own Galaxy, the Milky Way, then we do about the other galaxies millions of light years away which fill the "nearby" universe. Optical astronomers have been handicapped in studying the large-scale structure of the Galaxy because of the existence of vast clouds of obscuring matter in the form of interstellar dust which hang like dark curtains in the plane of the Galaxy. Fortunately, electromagnetic radiation at other wavelengths, particularly radio, infrared and gamma-ray wavelengths, can reach us from all parts of the Galaxy without being significantly attentuated by interstellar gas and dust.

One of the most significant results of the new astronomy is the mapping of the gamma-ray emission over large portions of the sky by the NASA Small Astronomy Satellite SAS-2[1,2] and mapping in progress by the similar European COS-B satellite. Some of the results obtained by SAS-2 are shown in Figures 1 and 2.

The general features of the SAS-2 sky maps are as follows:

On the largest scale, the cosmic gamma-radiation consists of two components: an extragalactic background and a galactic component. The extragalactic background radiation, coming from all directions, is most probably cosmological, originating at a time when the universe was much younger then it is now. This can be concluded from the intensity, energy spectrum and isotropy of the radiation. Indeed, this radiation may have resulted from the annihilation of large amounts of antimatter in the universe, an intriguing possibility[3,4,5].

Superimposed on this background radiation is a bright band of radiation lying in the plane of the Milky Way which originates in our own galaxy. This galactic radiation has an energy spectrum which is different from that of the cosmic background gamma-radiation. The galactic radiation varies in brightness along the galactic plane, being most intense in a band within 35° of the galactic center where it is almost 10 times brighter than in directions away from the galactic center (see Fig. 1). It is produced primarily by cosmic rays as they collide with interstellar gas atoms.

The galactic gamma-radiation, which this article addresses, can be broken up into near and far components. The near component appears to be associated with a relatively local system of dark nebulae, gas clouds and groups of hot young stars known as Gould's belt. The intensity and spatial distribution of gamma-radiation in this near component are about what one would expect if the gamma-rays are produced by collisions of local cosmic rays with nuclei of interstellar gas atoms in Gould's belt. The far component will be discussed in detail a bit later. It originates in the inner Galaxy, about 15,000 light years away, and its radiation is very narrowly confined to the galactic plane.

Two young nearby pulsars, the famous ones in the Crab Nebula (see Fig. 3) and Vela supernova remnants are seen as very bright pulsating γ-ray sources. There is another γ-ray source of unknown nature which is as bright in gamma-radiation as the Crab Nebula pulsar, located about 12° away from the Crab Nebula in the constellation Gemini. This source also pulsates but with a period of about 59 seconds, about 2000 times more slowly than the Crab Nebula pulsar. There are also indications of some weaker sources reported by the COS-B team[6]. One other possible source is the X-ray source in the constellation Cygnus known as Cygnus X-3[7].

THE GREAT GALACTIC RING

The contour map shown in Figure 1 shows that most of the cosmic gamma-radiation made up of photons having an energy greater than 100 million electron volts (MeV) comes from the direction of the Milky Way, i.e., the plane of the galactic disk defined as galactic latitude $b = 0°$. Two other prominent features in the map, associated with the far component, are discernable: (1) a bright extended region of gamma-ray emission in the direction of the galactic center (ℓ=0°, b=0°) and (2) a prominent ring of emission seen tangentially at galactic longitudes ℓ of about 35° and 335°. These features can also be seen in figure 2 which graphs the total intensity of cosmic gamma-rays at various longitudes that are produced at galactic latitudes within 10° of the galactic plane. Idealizations of the peak in the emission coming from the galactic center region and the generally high intensity coming from within 30° to 40° of the galactic center are shown schematically in figure 4. The latter large-scale feature, as depicted in figure 4, has the characteristic shape of a shallow letter M, which is what is seen when one is observing emission from an annular region or two dimensional shell. This is demonstrated in figure 5. We observe the ring of emission through lines of sight at various galactic longitudes. When we are looking almost tangentially at the ring, near ℓ_M, we observe the most intense emission along the galactic plane because we are then looking through more of the emission ring. As we look in toward the center (ℓ=0) the emission drops off, but it doesn't drop off completely because we are always looking at some part of the emission ring. The three dimensional analogue of this ring is the spherical shell of a planetary nebula such as the Ring Nebula (see figure 6), which appears to be brightest in a ring shaped region near the extremity of the spherical shell.

If one geometrically unfolds the longitude distribution of galactic γ-rays (Fig. 2), a distribution of galactic gamma-ray emission as a function of galactic radial distance can be obtained. The one which I derived is shown in figure 7[5]. The emission is shown separately for the two halves of the galactic plane from 0° to 180° (positive longitudes) and 180° to 360° (negative longitudes). Both sides of the Galaxy show the region of intense emission near the galactic center (R=0) and the bright ring of emission centered between 15,000 and 20,000 light years galactocentric radius. This defines a large-scale structural feature of the Galaxy, unknown before a few years ago, which I will call the "Great Galactic Ring".

The two prominent large scale galactic features, *viz.*, the central emission region and ring, appear to have quite different origins, different both in the physics of gamma-ray production and in the astronomical features in the Galaxy in which they arise.

γ-RAYS FROM COSMIC RAYS

There are three basic physical mechanisms most responsible for the production of gamma-rays in the Galaxy.[8] The first two processes involve the collisions of cosmic-ray nuclei and electrons with nuclei of interstellar gas atoms. Cosmic rays and gas in interstellar space consist of about 8 hydrogen atoms to every helium atom and a tiny (about a tenth of a percent by number) admixture of heavier elements. Thus, most of the collisions taking place in interstellar space involve nuclei of hydrogen atoms, i.e., simple protons. These collisions will produce neutral pi-mesons (or pions, sympol π°) if the energy involved in the collisions is above 300 MeV. The π° mesons, among all particles produced in such interactions, are by far the most likely progenitors of cosmic gamma-rays; they decay almost 100 per cent of the time into two gamma-rays apiece, each of which would have an energy of 67.5 MeV (half the π° mass times c^2, c being the speed of light) if the π° meson were not moving. However, since the meson is generally moving near the speed of light, the laws of special relativity tell us that the gamma-rays which we observe will have a range of energies, with a geometric mean energy of 67.5 MeV.

The second gamma-ray production process, electron bremsstrahlung, involves the deceleration of a cosmic-ray electron in the electric field of an interstellar gas nucleus. Bremsstrahlung in German means braking radiation. As a consequence of this type of interaction, energy lost by the electron can go into the creation of gamma-ray photons with momentum being conserved by the recoil of the nucleus.

The third process involves the collision of a cosmic ray electron with a photon of starlight radiation. The starlight photon has a typical energy of the order of an electron volt. However, as a result of the collision, the final energy of the photon can be boosted to as much as 100 MeV or more. All of this is, of course, at the expense of the electron. Collisions of this type, where energy is exchanged between electrons and photons, are known as Compton interactions in honor of their discoverer Arthur Holly Compton.

Since the effective cross sections for these collisions, i.e., the production rates per nucleus or per photon for all of these processes are well known, the amount of interstellar gamma-ray production from each of these processes can be calculated. Because the SAS-2 and COS-B satellite detectors are sensitive primarily to gamma-rays with energies above 100 MeV, the rates for producing gamma-rays in this energy range are particularly useful. Figure 8 shows the production rates for the various processes involved, estimated for the solar galactic neighborhood, 33,000 light years from the galactic center, where the average density of interstellar hydrogen gas is estimated to be about 1 atom per cm^3 and the average starlight radiation density is about 1/2 eV per cm^3 (5). The intensities of cosmic ray nucleons are obtained by direct measurements but the intensity of cosmic ray electrons must be inferred indirectly and is more uncertain. The estimates indicate that the decay of π° mesons is most probably the dominant process for producing cosmic gamma-rays above 100 MeV in our neighborhood of the Galaxy.

HYDROGEN AND CARBON MONOXIDE RADIO EMISSION

What of the interstellar gas and radiation fields in other parts of the Galaxy? If we can estimate these, we can use the satellite observations of the galactic gamma-rays to determine the intensity of cosmic rays in distant parts of the Galaxy and thereby learn something about the origin of cosmic rays, namely, their birthplaces.

We know now that the vast bulk of the interstellar gas is in the form of hydrogen. Fortunately, hydrogen in atomic form can be detected by radio telescopes because of its characteristic radio spectral line at 21cm wavelength. However, hydrogen in molecular form does not emit radiation at this wavelength. Indeed, the strongest spectral features from the H_2 molecule are in the ultraviolet (UV) band of the electromagnetic spectrum. This radiation has been studied using a UV telescope aboard the Copernicus satellite[9] which has taught us much about our "local" galactic neighborhood. Unfortunately, the UV portion of the electromagnetic spectrum is not useful for large scale galactic structure studies because this radiation can only travel through a small fraction of the Galaxy, a mere 2,000 or 3,000 light years, before being absorbed by the interstellar dust. The H_2 molecule also has spectral features in the infrared portion of the spectrum. Such radiation can reach us from much larger distances, but the emission features are so weak that we cannot make use of them for galactic mapping with present technology.

Since the H_2 molecule is the most stable form of hydrogen at low temperature and since it is expected to be the predominant form of hydrogen in cool clouds with densities greater than a few hundred atoms per cm^3, it is important to determine the abundance and distribution of H_2 on a galactic scale. Indirect means have recently been employed in order to accomplish this. Radio emission from other molecules coexisting with H_2 in cool interstellar molecular gas clouds can be used to trace H_2 in the Galaxy. Because of its relative abundance as compared with other interstellar molecules (excluding H_2), the CO molecule has become a useful H_2 cloud tracer. This molecule has a radio spectral line at 2.64mm. With the recent dvelopment of millimeter-wave radio telescopes and receiving equipment, surveys of the Galaxy at 2.64mm wavelength, comparable to those done at 21cm to study atomic hydrogen, have begun. Initial surveys were performed at the National Radio Astronomy Observatory 36 foot radio telescope on Kitt Peak in Arizona by two teams. The surveys were made by Scoville and Solomon[10] and by Burton et al.[11]. An additional survey has been made by Cohen and Thaddeus[12] using a millimeter-wave telescope perched on a New York City roof top. These surveys revealed that the galactic distribution of H_2 clouds is dramatically different from that of the more diffuse atomic hydrogen gas. Whereas the atomic hydrogen is quite uniformly distributed on a large scale in regions of the Galaxy between 13,000 and 46,000 light years galactocentric radius, falling off inside of 13,000 light years radius and outside of 46,000 light years radius, the H_2 clouds have a strongly varying radial distribution. They also fall off inside of 13,000 light years radius with the exception of a small nuclear region within 600 light years of the galactic center; they also become almost non-existent outside of 30,000 light years from the galactic center. However, the H_2 clouds are strongly concentrated in an annular region or ring, reaching a peak density at a radial distance of about 15,000 to 20,000 light years, the same place where the gamma-ray emission peaks - the Great Galactic Ring! The neighboring spiral galaxy in Andromeda may have a similar ring (see Figure 9).

The 21cm and 2.64mm surveys indicate that there is little gas, either in atomic or molecular form, inside of 13,000 light years from the galactic center, except for the 600 light year nuclear region. Thus, the central component of gamma-ray emission shown in figure 4 cannot be easily explained as due to interactions between cosmic rays and gas. Rather, the longitude profile of the central component appears to be similar to the distribution of densely packed old stars in the central galactic bulge. The distribution of old bulge stars has been calculated from dynamic models of the mass distribution in the Galaxy. It has also been recently observed in surveys of infrared radiation from these stars made by Ito et al.[13] and Hofmann et al.[14]. It thus seems a likely possibility that Compton interactions between cosmic ray electrons and the intense radiation field created by the densely packed stars in the galactic central bulge produce the central gamma-ray component. However, in the Great Galactic Ring, radiation from starlight is considerably lower in intensity and the interactions between cosmic rays and interstellar gas, i.e., the bremsstrahlung and pion-decay processes, are the predominent gamma-ray production processes.

GALACTIC GESTALT

Nicholas Scoville, Philip Solomon, Charles Ryter and I[15] and independently Mark Gordon and W. Butler Burton[16] have used the data obtained from the millimeter wave CO surveys to estimate the average density of H_2 in the Galaxy in the form of interstellar clouds as a function of galactocentric radius. These determinations indicate that the volume averaged H_2 density in the Great Galactic Ring of molecular clouds at 15,000 to 20,000 light years radius is about 4 to

5 atoms (2 to 2.5 molecules) per cm^3. There appears to be about the same amount of H_2 as atomic H in the Galaxy overall, with each component making up about 2 percent of the mass of the Galaxy. These components are distributed in such a way that the bulk of the atomic hydrogen is found in the outer parts of the Galaxy, whereas the vast bulk of interstellar H_2 is found in the inner regions of the Galaxy. This segregation of gas should also exist in other spiral galaxies and provides the clue to a mystery revealed some years ago when 21cm surveys of the atomic hydrogen in other spiral galaxies become possible.

Radio observations at 21cm wavelength have revealed that in most spiral galaxies the atomic hydrogen is predominantly found in regions of these galaxies lying outside of those where star formation is taking place (see, e.g., Fig. 10). Such regions of active star formation are evidenced by the existence of bright, young short-lived stars. If stars are formed from atomic hydrogen, why aren't the young stars in the same place where most of the gas appears to be?

It now appears that the answer to this question is that star formation takes place in cool dense H_2 clouds, invisible in 21cm radio surveys. These clouds, which make up the bulk of interstellar gas in the inner regions of the Galaxy where star formation processes are most active, were until recently hidden beneath our observational horizon like the bulk of an iceberg lurking beneath the North Atlantic. The H_2 clouds thus provide the missing link in understanding the dynamics of star formation in the Galaxy. The relatively nearby Great Nebula in Orion, whose inner part is shown in Figure 11, is a cloudy dusty region which is an active galactic nursery. Such regions should be much more common in the Great Galactic Ring.

Giant regions of ionized hydrogen called HII regions, ionized by the ultraviolet light of hot, young stars, can be detected by characteristic radio spectral emission features which they produce. These regions also mark the birthplace of stars. Radio observations have shown that the giant HII regions also reach a peak density in the Great Galactic Ring[17]. Surveys of the remnants of supernova explosions, detectable by the characteristics of their radio spectra, and recent galactic surveys of radio pulsars indicate that these inhabitants of the Galaxy also reach a peak density in the Great Galactic Ring[18-20]. Since pulsars are associated with supernova remnants such as the Crab Nebula (see Figure 3), and since a supernova explosion is thought to mark the final explosion stage in the evolution of massive short-lived stars, a natural explanation for all of these similarities in galactic distribution suggests itself. We are looking at where the young objects in the Galaxy are[21].

The origin of the Great Galactic Ring must be intimately related to the general problem of the origin of galactic spiral structure. A theory which has had considerable success in attempting to explain the persistence of spiral arms in galaxies is known as the "density wave theory". A consequence of this theory is that interstellar gas, as it rotates around the Galaxy, passes through spiral-shaped wavelike regions of relatively stronger gravitational force where it is compressed.[22] In the inner Galaxy, the rotational speed of the gas is greater and the compressions are more frequent than in the outer galaxy. Also, the rotational velocity of the gas can become greater than the speed of sound in the inner Galaxy[23]. Supersonic shock waves can then form, causing irreversible compressions of gas into the form of relatively dense molecular clouds and later leading to the formation of bright young stars and HII regions in spiral patterns. This may help explain why molecular clouds are far more abundant in the inner Galaxy where "strong" supersonic compressions are probably occurring, whereas, in the outer galaxy, where "weak" subsonic compressions are occurring, most of the gas is in the form of more diffuse atomic clouds.

THE BIRTHPLACE OF COSMIC RAYS

A final piece to the puzzle comes from an analysis of the galactic gamma-ray emission surveys. This analysis suggests that the increase in interstellar gas in the Great Galactic Ring *alone* is not sufficient to explain the increased gamma-ray emission in that part of the Galaxy. An accompanying increase in the cosmic ray intensity in the Great Galactic Ring is also called for[24]. The relative increase in cosmic-ray intensity required is, furthermore, the same as the relative increase in supernova remnants and pulsars in the Ring as found in recent radio surveys. The gamma-ray observations also indicate that the cosmic-ray intensity drops off rapidly in the outer parts of the Galaxy as do the numbers of supernova remnants and pulsars. The striking resemblance between the distribution of cosmic rays implied by the gamma-ray data and the distribution of supernova remnants and pulsars found by radio astronomers gives strong support to the hypothesis that most cosmic rays are born in our Galaxy, being produced either in supernova explosions or the pulsars which result from these cataclysmic events.

The supernova hypothesis for the origin of cosmic rays, was put forth by Walter Baade and Fritz Zwicky in the 30's. It gained support in the early 50's when the Russian astrophysicist, Iosef Shklovsky, proposed that cosmic ray electrons, spiraling in the magnetic field of the Crab Nebula supernova remnant, produced its radio emission and diffuse light (see Figure 3). This radiation, which is seen in accelerators, is known as synchrotron radiation. The supernova origin hypothesis has become quite popular. Nevertheless, several distinguished astrophysicists have advocated an opposing view that cosmic rays are extragalactic in origin, being produced in powerful radio galaxies millions of light years.

As a summary of the picture of galactic activity which is now emerging, the flow diagram shown in Figure 12 illustrates the cycle of activity in a region of active star formation. Groups of hot young stars, called OB associations, condense out of cool dusty molecular hydrogen clouds. The most massive of these stars are by far the hottest and brightest, ionizing the gas around them to create HII regions. They burn up their nuclear fuel in a mere 10 million years or so as compared with 10 billion years for a star like the Sun. These massive stars are cosmic time-bombs; at the end of this 10 million year period they explode into supernovae. Cosmic rays are produced either in the supernova explosions themselves or in the pulsars which they can leave behind. Cosmic ray electrons are known to be produced by pulsars since we see their radio emission. Cosmic ray pressure may help precipitate more dense molecular clouds out of the interstellar medium, as indeed pressure from the supernova explosions themselves may do[25]. The cosmic rays may also help to ionize the gas in the giant HII regions. Finally, the cosmic rays, colliding with gas atoms in the molecular clouds, produce gamma-rays.

Figure 13 illustrates how the distribution of cosmic rays in and around our galaxy might appear as seen from outside. The lines represent contours of equal cosmic ray intensity as seen edge-on in cross section[26].

According to this picture, the cosmic rays originate in active regions throughout the galactic disk, but are produced more frequently in the Great Galactic Ring, shown in figure 13 in cross section as the two "eyes" on either side of the galactic center. The cosmic rays then diffuse out in all directions, dropping off in intensity by a factor of two at distances of 10,000 light years or less from the galactic plane. If the cosmic radiation originated outside the Galaxy, its galactic distribution would be uniform and the γ-ray map of the Galaxy would not be as bright looking toward the galactic center nor as dim in the outer regions of the Galaxy.

What we have learned from gamma-ray astronomy in the 70's reconfirms Harlow Shapley's conclusion in 1918 that we live far from the geometric center of the galaxy. In addition, the new results have shown that our home in the galactic suburbs is relatively quiet; most of the activity, new stars, supernova explosions, pulsars, cosmic rays, etc., are found thousands of light years away, much closer to the galactic center. We are only on the quiet outer edge of the vast system of stars which we call the Milky Way.

References

1. Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Bignami, G. F., Ögelman, H., Özel, M. E. and Tümer, T. 1975 Astrophys. J. 198, 163.
2. Thompson, D. J., Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Bignami, F. F., Lamb, R. C., Ögelman, H., Özel, M. E. and Tümer, T. 1977 in The Structure and Content of the Galaxy and Galactic Gamma Rays, NASA CP-002 (Washington: U.S. Gov't. Printing Office) p. 3.
3. Stecker, F. W., Morgan, D. L. and Bredekamp, J. 1971, Phys. Rev. Lett. 27, 1469.
4. Stecker, F. W. 1975 in Origin of Cosmic Rays, ed. J. L. Osborne and A. W. Wolfendale (Dordrecht-Holland, Reidel Pub. Co.) p. 267.
5. Stecker, F. W. 1977 Astrophys. J. 212, 60.
6. The COS-B collaboration 1977 Nature 269, 494.
7. Lamb, R. C., Fichtel, C. E., Hartman, R. C., Kniffen, D. A. and Thompson, D. J. 1977 Astrophys. J. 212, L63.
8. Stecker, F. W. Cosmic Gamma Rays (Baltimore: Mono Book Co.) 1971.
9. Spitzer, L., Drake, J. F., Jenkins, E. B., Morton, D. C., Rogerson, J. B. and York, D. G. 1973, Astrophys. J. 181, L116
10. Scoville, N. Z. and Solomon, P. M. 1974, Astrophys. J. 187, L67.
11. Burton, W. B., Gordon, M. A., Bania, T. M. and Lockman, F. J. 1975, Astrophys. J. 202, 30.
12. Cohen, R. S. and Thaddeus, P. 1977, Astrophys. J. 217, L115.
13. Ito, K., Matsumoto, T. and Uyama, K. 1977, Nature 265, 517.

14. Hofmann, W., Lemke, D. and Thum, C. 1977, Astron. and Astrophys. 57, 111.

15. Stecker, F. W., Solomon, P. M., Scoville, N. A. and Ryter, C. E. 1975, Astrophys. J. 201, 90.

16. Gordon, M. A. and Burton, W. B. 1976, Astrophys. J. 208, 346.

17. Lockman, F. J. 1976, Astrophys. J. 207, 429.

18. Kodaira, K. 1974, Pub. Astr. Soc. Japan 26, 255.

19. Hulse, R. A. and Taylor, J. H. 1975, Astrophys. J. 201, L55.

20. Seiradakis, J. 1977, in The Structure and Content of the Galaxy and Galactic Gamma Rays NASA CP-002 (Washington: U. S. Gov't. Printing Office) p. 265.

21. Stecker, F. W. 1976, Nature 260, 412.

22. Roberts, W. W., Jr., Roberts, M. S. and Shu, F. H. 1975, Astrophys. J. 196, 381.

23. Burton, W. B. 1976, Ann. Rev. Astron. Astrophys. 14, 275.

24. Stecker, F. W. 1975, Phys. Rev. Letters 35, 188.

25. Ögelman, H. B. and Maran, S. P. 1975, Astrophys. J. 209, 124.

26. Stecker, F. W. and Jones, F. C. 1977, Astrophys. J. 217, 843.

27. Rots, A. H. and Shane, W. W. 1975, Astron. and Astrophys. 45, 25.

Figure Captions

Fig. 1 γ-ray contour map of the inner galaxy obtained by the SAS-2 satellite. The map is really "out of focus" because of the limited resolution of the γ-ray "telescope". The most intense radiation from the inner Galaxy is probably concentrated within less than 2° from the galactic plane (0° latitude).

Fig. 2 γ-ray intensity versus galactic longitude for the inner galaxy as obtained by SAS-2.

Fig. 3 The Crab Nebula, the debris from a giant stellar explosion or supernova. The light from the nebula comes from cosmic-ray electrons produced by the dense spinning remnant core of the ex-star. The core object, a neutron star, beams pulses of radiation at us, acting like the spinning light atop a police car. It is called a pulsar. (Hale Observatories).

Fig. 4 Schematic idealized longitude distribution for the inner galaxy showing the central and ring components.

Fig. 5 Schematic of how an M-shaped γ-ray longitude distribution is produced by a ring source. As the telescope scans the Galaxy at longitude ℓ, it sees emission being produced along the entire line-of-sight. At tangential directions, just inside of ℓ_M, the telescope sees emission coming from a larger portion of the ring then it sees near the center (ℓ=0°). This accounts for why the peak γ-ray fluxes are seen near ℓ_M.

Fig. 6 The Ring Nebula in the constellation Lyra (Hale Observatories). The central star is surrounded by a roughly spherical shell of light-emitting gas. Because one looks through the edge of the shell, by analogy to the two dimensional case of figure 5, the edge appears brighter than the center and the shell takes on the appearance of a ring.

Fig. 7 Radial distributions of γ-ray emission for both halves of the galaxy. Note that in addition to the prominent peak at the galactic center and in the 15,000-20,000 light year region corresponding to the Great Galactic Ring, there may be secondary features near 10,000 and 25,000 light years radius. It has been suggested by Carl Fichtel and co-workers[1] that such features represent emission from spiral arms of the Galaxy. Such secondary features may also be caused by other objects such as stellar γ-ray sources within the Galaxy. Future satellite observations may help to pin this down.

Fig. 8 γ-ray production rates for the "local" galactic neighborhood.

Fig. 9 The inner region of our sister spiral galaxy the Great Galaxy in Andromeda (Hale Observatories). This galaxy may also have a great ring of gas clouds, dust clouds and active star formation. Note the ring of dark dust clouds which is particularly prominent in the upper left-hand portion of the picture.

Fig. 10 The distribution of (a) atomic hydrogen and (b) optical starlight radiation in the spiral galaxy M81. The hydrogen distribution was obtained in a high resolution 21cm radio survey by Rots and Shane[27]. Note that the atomic hydrogen is more abundant in a region outside of where most of the stars are found.

Fig. 11 The Great Nebula in Orion, a contrasting region of dense cool molecular clouds and dust juxtaposed with bright young stars and hot ionized gas clouds, marks an active region of star formation. The new gamma-ray and radio surveys indicate that such regions should be more abundant in a great ring-shaped region of the inner Galaxy. (Photo, Hale Observatories).

Fig. 12 The flow diagram shown above illustrates the cycle of inter-related activity in a region of active star formation as explained in the text. Such regions are much more common in the area of the Great Galactic Ring.

Fig. 13 An illustration of how our galaxy might appear edge-on showing idealized cross sectional contours of equal cosmic ray intensity[26]. The cross sections bisect the Great Galactic Ring on either side of the geometrical center where the cosmic ray intensity reaches a maximum. (Photo, without contour lines, courtesy of Hale Observatoires).

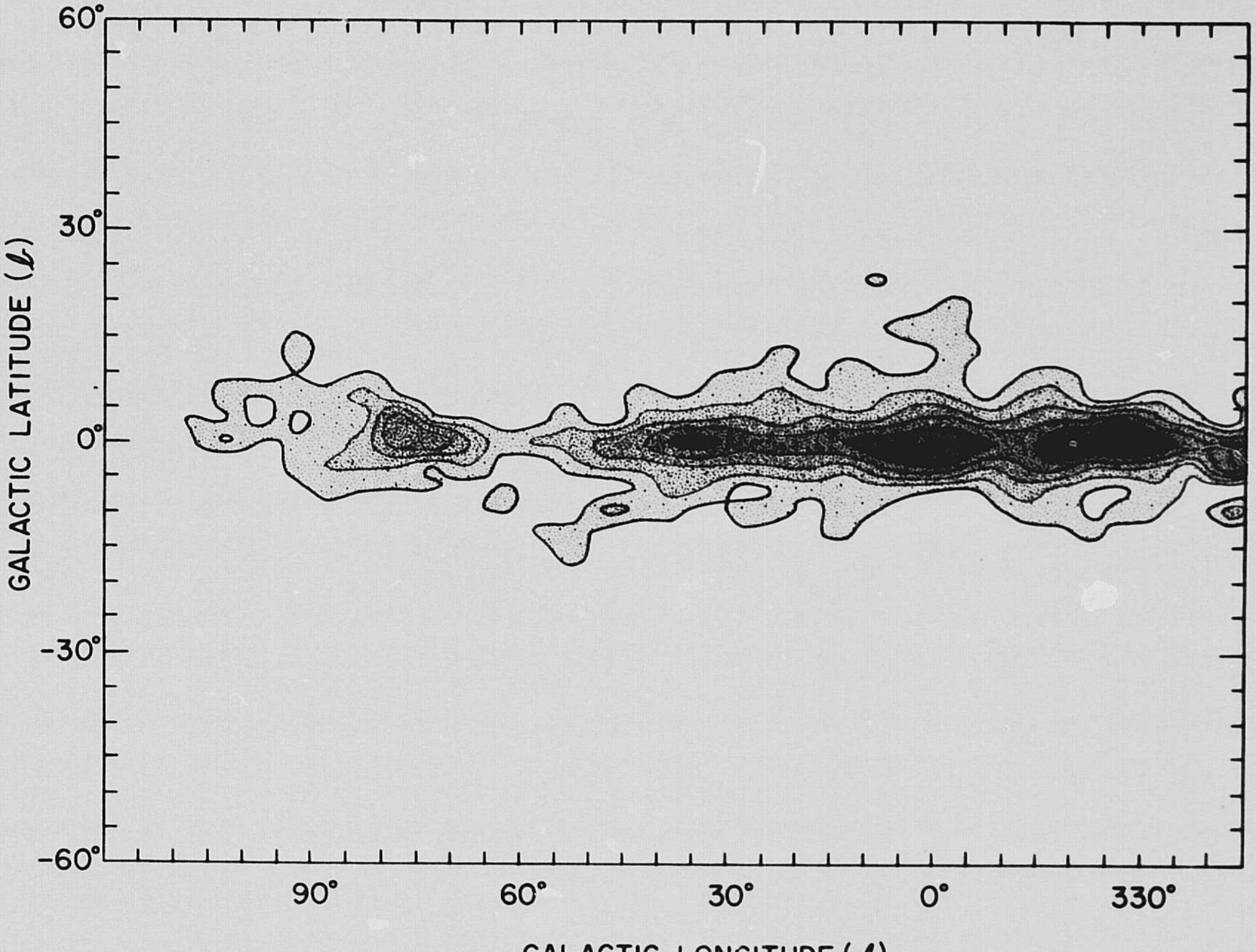
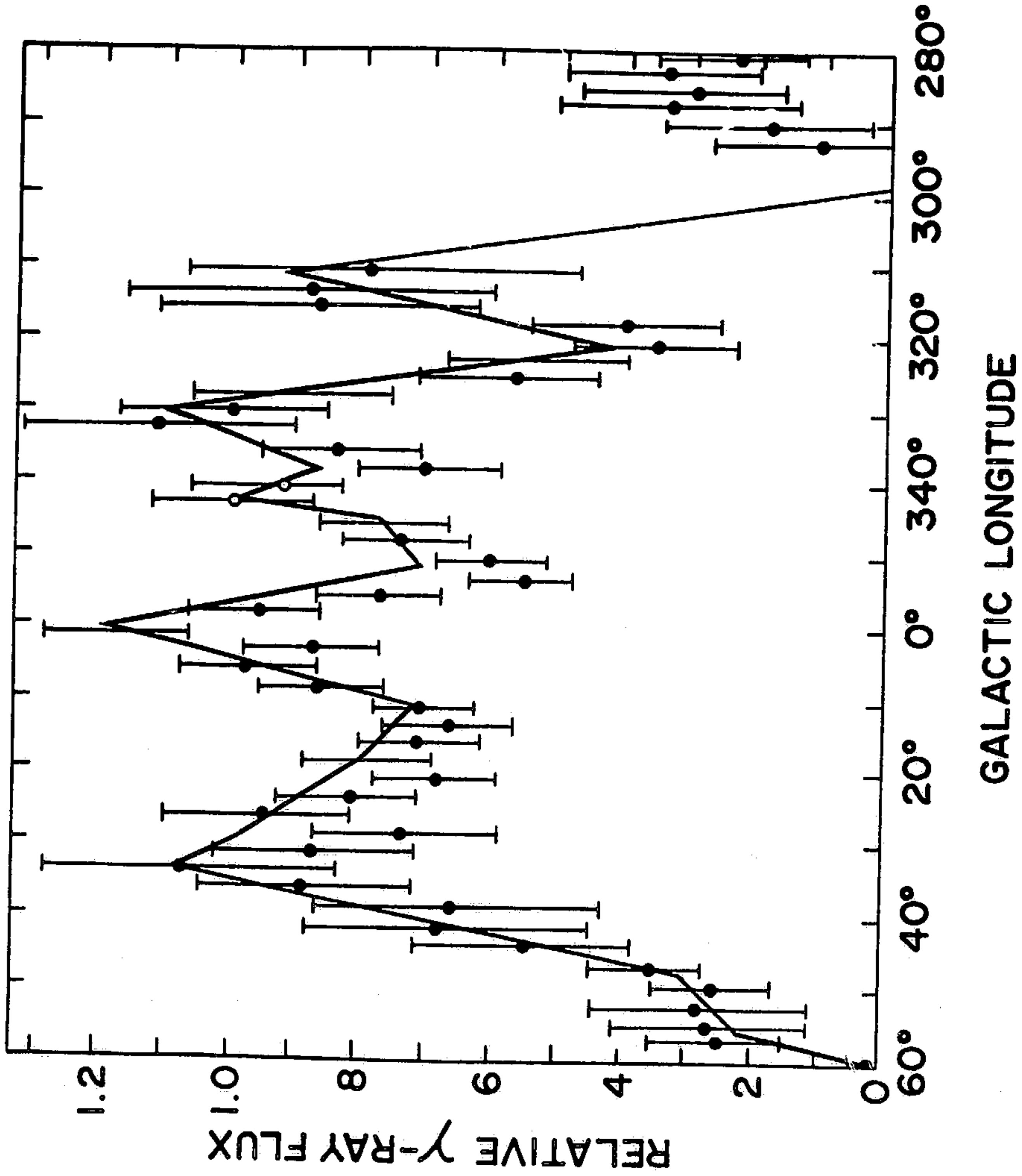

60°
30°
0°
-30°
-60°
GALACTIC LATITUDE (ℓ)
90°
60°
30°
0°
330°
GALACTIC LONGITUDE (ℓ)

Fig. 2



RELATIVE γ-RAY FLUX
GALACTIC LONGITUDE
60°
40°
20°
0°
340°
320°
300°
280°
0
2
4
6
8
1.0
1.2

Fig. 3.

The Crab Nebula

Fig. 4

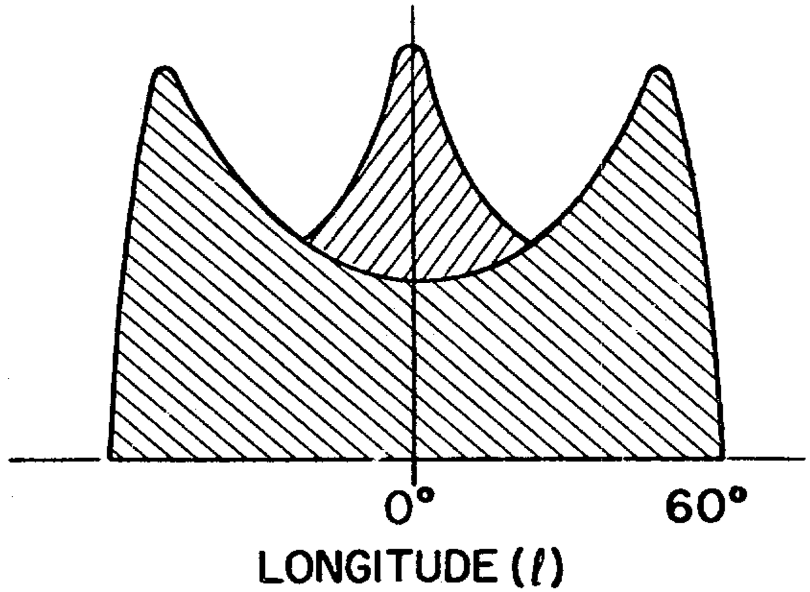


Fig. 5

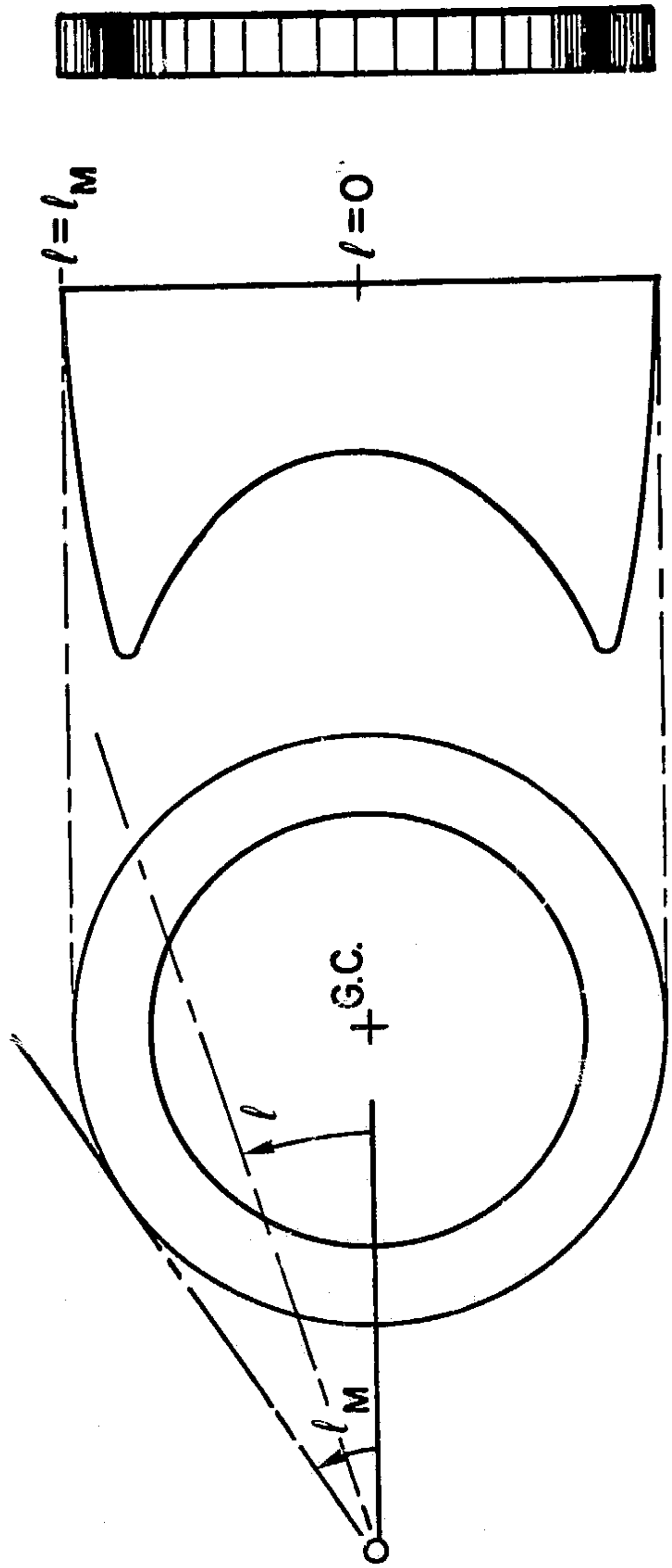
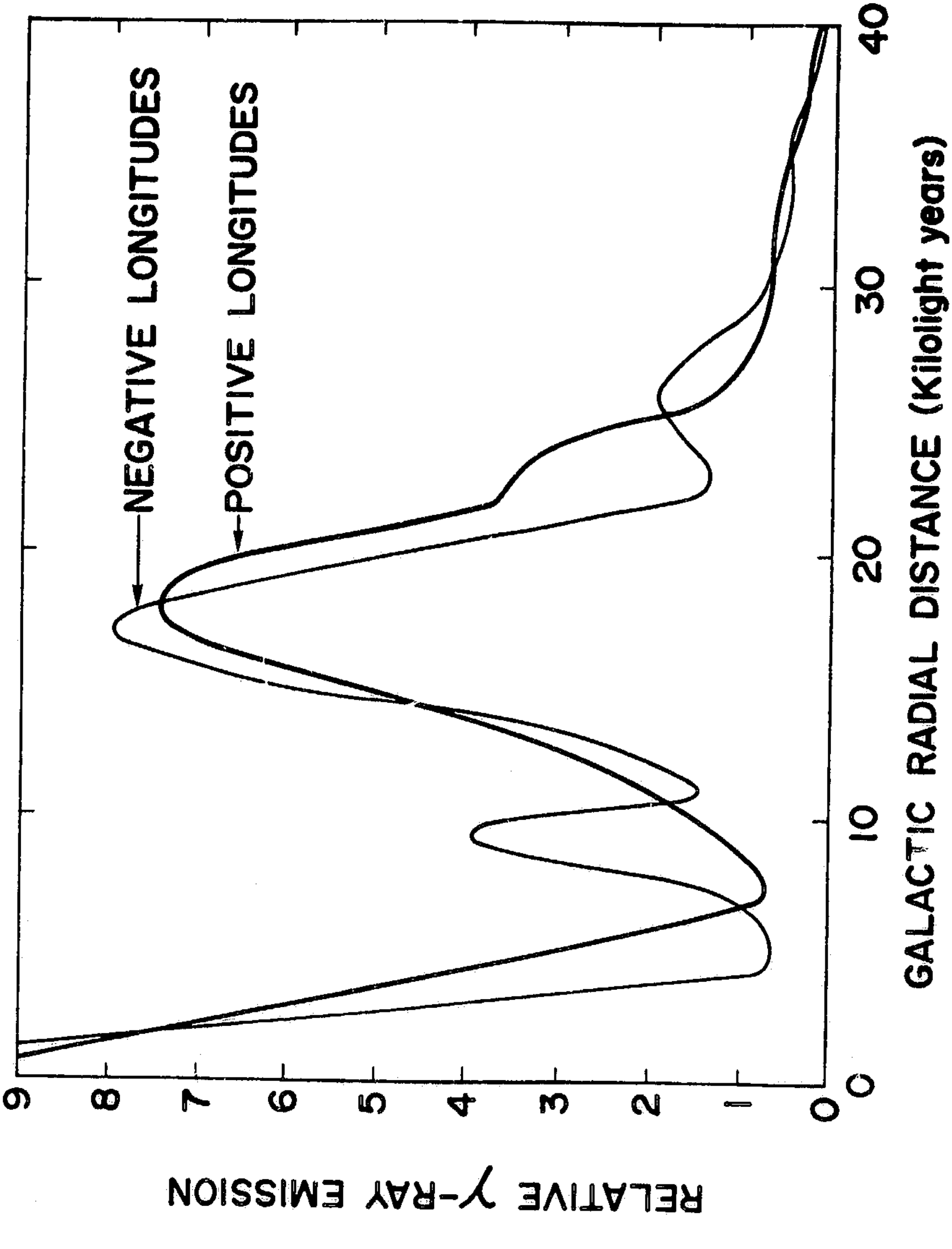


Fig. 6

The Ring Nebula

Fig. 7


NEGATIVE LONGITUDES
POSITIVE LONGITUDES
GALACTIC RADIAL DISTANCE (Kilolight years)
RELATIVE γ-RAY EMISSION
0
10
20
30
40
0
1
2
3
4
5
6
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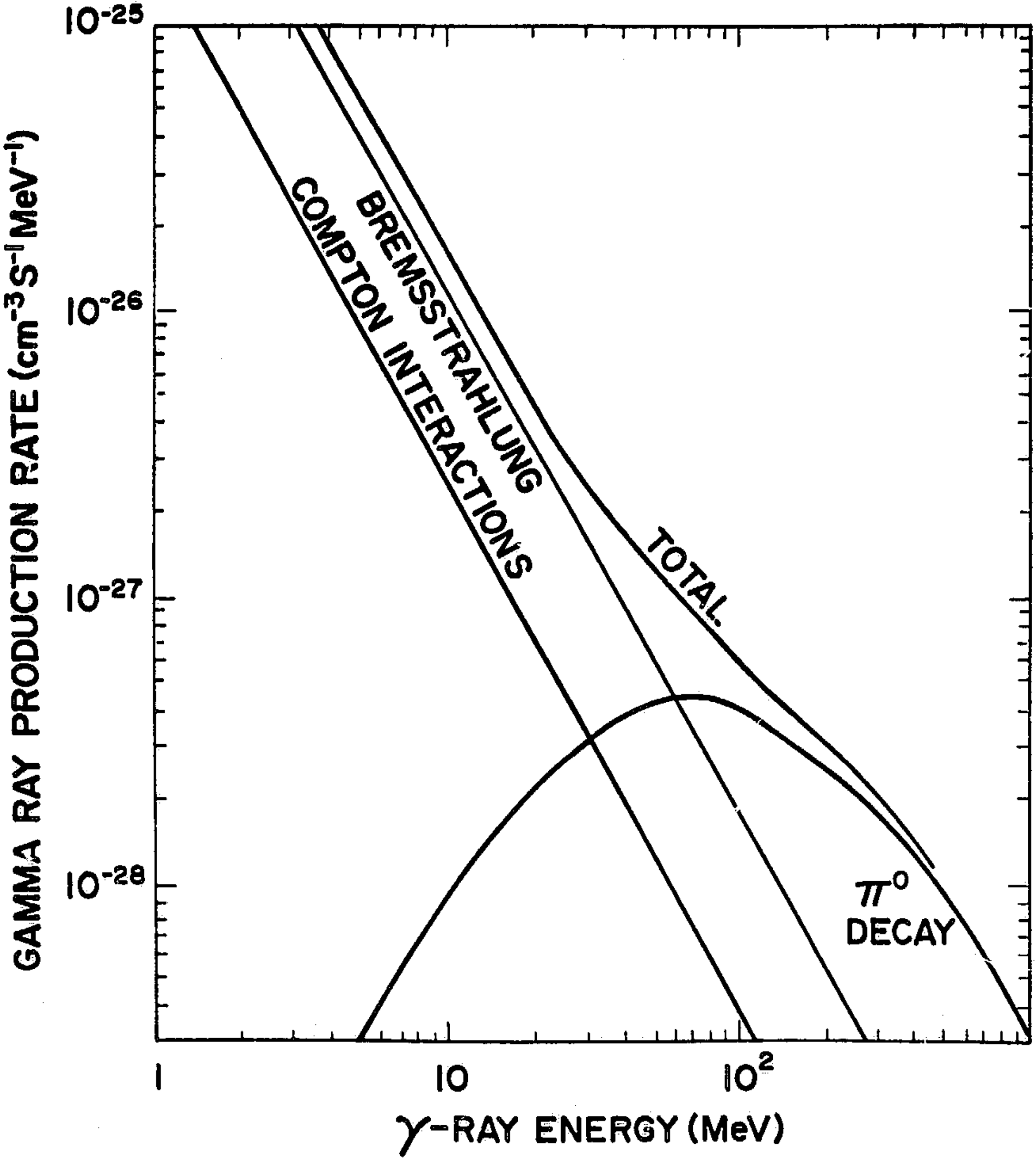
8
9

Fig. 8

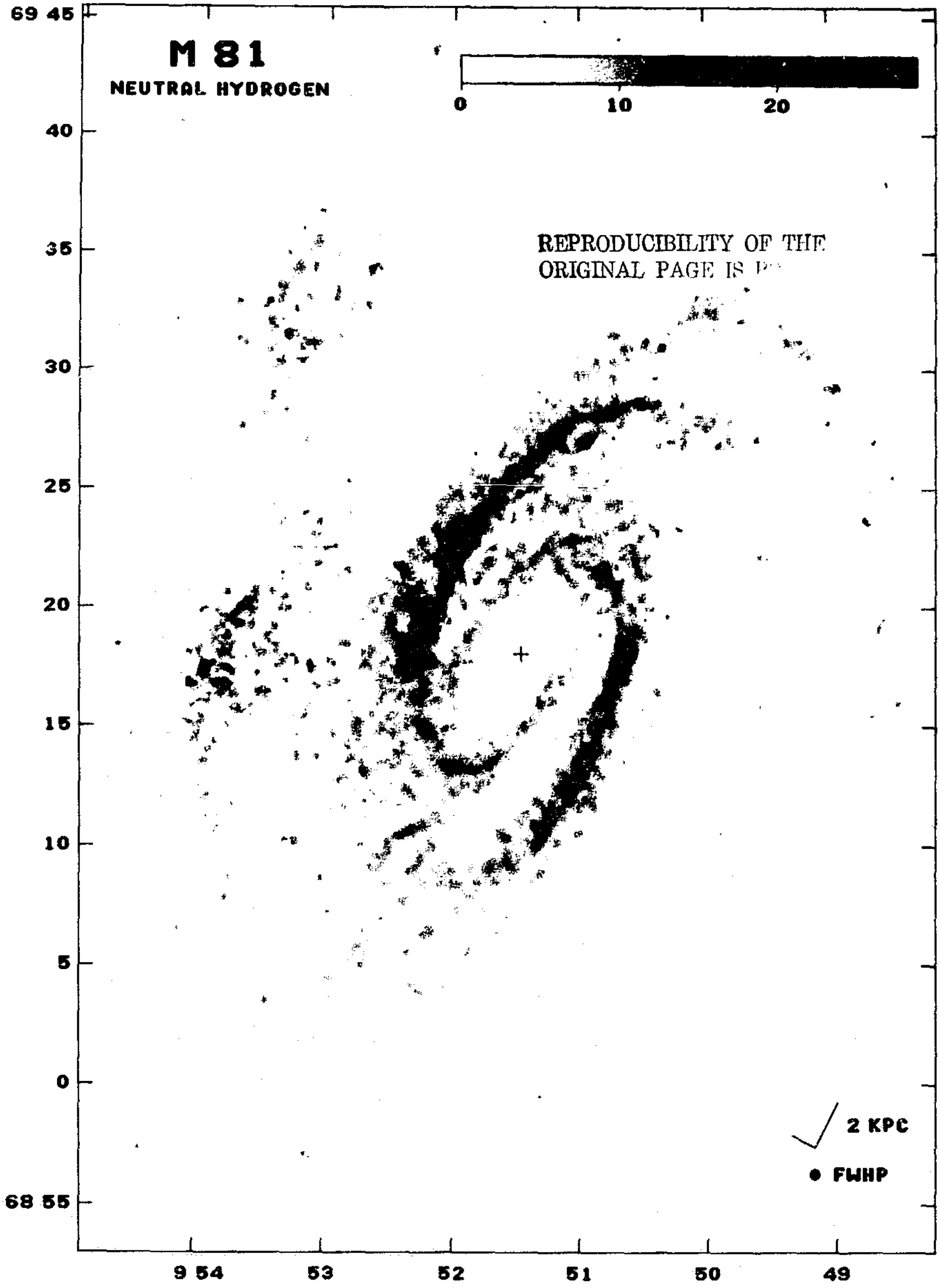


GAMMA RAY PRODUCTION RATE (cm⁻³S⁻¹MeV⁻¹)
10-25
10-26
10-27
10-28
BREMSSTRAHLUNG
COMPTON INTERACTIONS
TOTAL
π0 DECAY
1
10
10²
γ-RAY ENERGY (MeV)

Fig. 9

The Andromeda Galaxy M31

(inner region)



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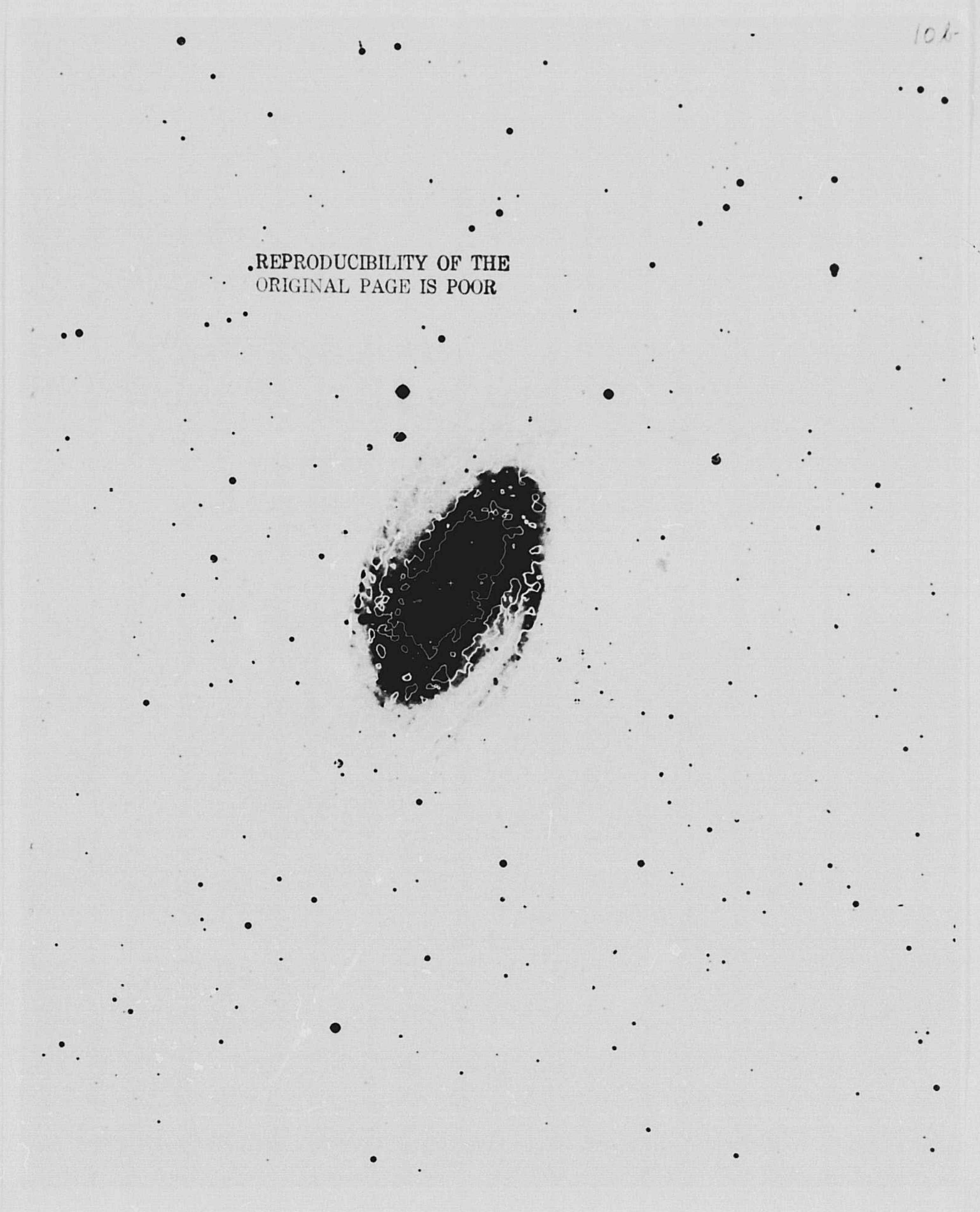
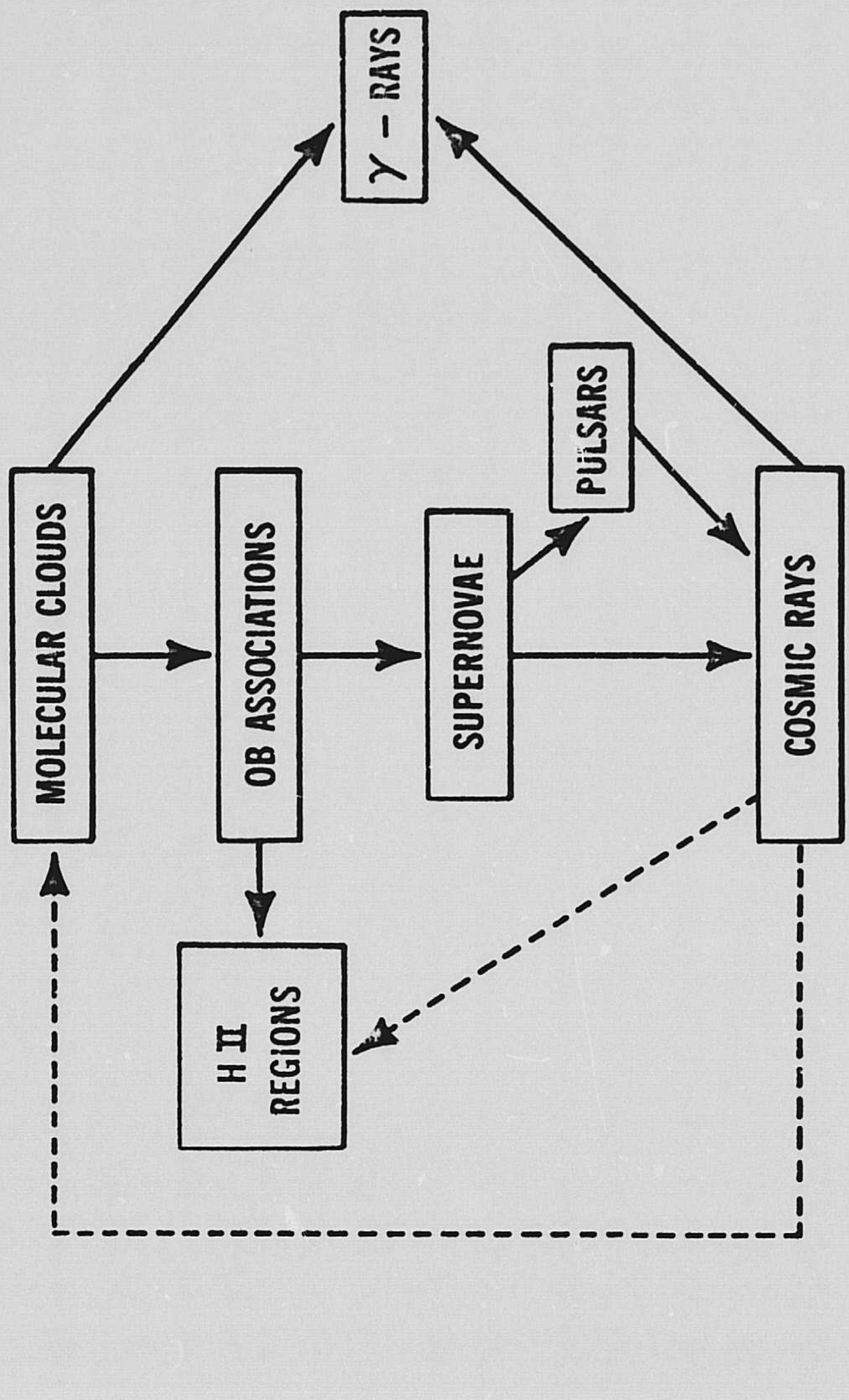


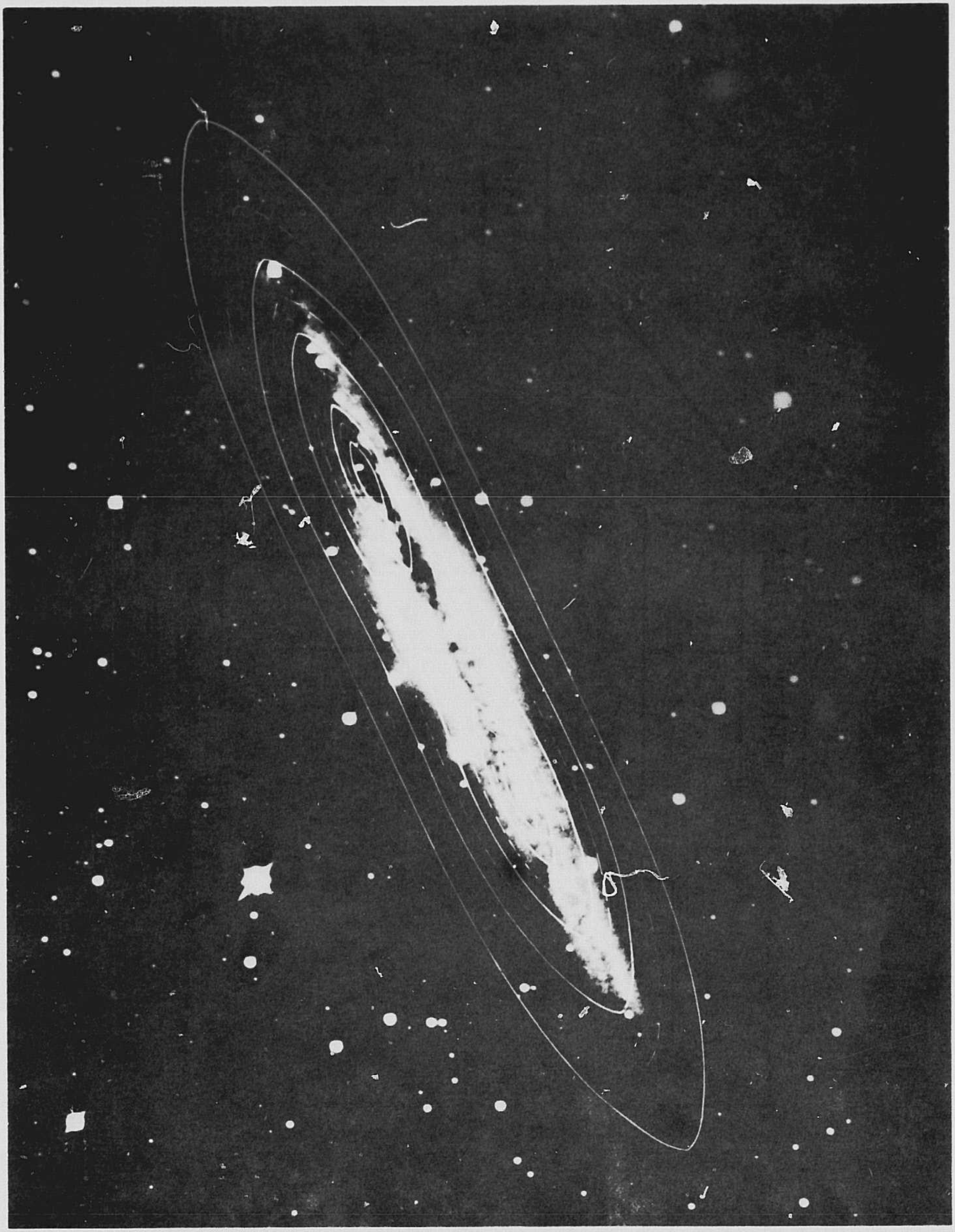
Fig. 11

The Orion Nebula

Fig. 12



γ − RAYS
MOLECULAR CLOUDS
OB ASSOCIATIONS
SUPERNOVAE
PULSARS
COSMIC RAYS
H II REGIONS



BIBLIOGRAPHIC DATA SHEET

1. Report No. TM 79535	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Gamma-Ray Astronomy and the Origin of Cosmic Rays		5. Report Date April 1978
		6. Performing Organization Code 660
7. Author(s) F. W. Stecker		8. Performing Organization Report No.
9. Performing Organization Name and Address Laboratory for High Energy Astrophysics Code 660		10. Work Unit No.
		11. Contract or Grant No.
		13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address		
		14. Sponsoring Agency Code

15. Supplementary Notes

To be published in American Scientist

16. Abstract

New surveys of galactic gamma-ray emission together with millimeter wave radio surveys indicate that cosmic rays are produced as the result of supernova explosions in our Galaxy with the most intense production occurring in a Great Galactic Ring about 35,000 light years in diameter where supernova remnants and pulsars are concentrated.

17. Key Words (Selected by Author(s)) cosmic rays, gamma ray astronomy, galactic structure, supernovae, pulsars, interstellar medium	18. Distribution Statement

19. Security Classif. (of this report) UN	20. Security Classif. (of this page) UN	21. No. of Pages 36	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22151.

GSFC 25-44 (10/77)